Rehabilitation and Protection of Watershed Ecosystems Using Institutions and Intelligent Agent Simulations

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Objectives

Public officials and citizens face difficult knowledge and information problems in rehabilitating and protecting watershed ecosystems. Two of the more prominent management approaches for governing watersheds - integrated, comprehensive management and community-based management are limited in coping with watershed problems that emerge at different scales. Furthermore, most modeling efforts in the social and natural sciences do not explicitly incorporate human behavior. Thus, public officials and citizens struggle to understand the interactions among individuals, land use and water use ordinances and regulations, and watershed ecosystem responses. This project proposes to address these knowledge and information problems by designing dynamic models that are accessible to public officials and citizens that incorporate land and water uses, the effects of those uses on watershed ecosystems, and human and ecosystem responses to different sets of land use and water use ordinances and regulations.

The complex, interrelated causes of watershed degradation emerge from several sources. First, most rivers and streams have been re-engineered, through channelization, dams, embankment stabilization, and a host of other activities, each of which alters water flows and damages riparian areas. Second, point and non-point source pollution degrades water quality and imperils species and habitat dependent on water. Third, water diversions for human uses reduce or eliminate stream flows endangering species and habitat. The effects of these intensive human uses are not localized. They effect all forms of life in a watershed because of the structure of watersheds and watershed ecosystems. All inhabitants of a watershed are linked spatially and temporally. Upstream and downstream users interact and affect one another. Floodplain and riparian users interact with, effect and are effected by upland users. The hydrological connections between surface and ground water tie together the users of those waters. And, all of these interactions are dynamic; they change over time.

While watersheds are complex inter-related ecological and hydrological systems subject to diverse inter-related threats, management and policy approaches are generally fragmented. First, many different political jurisdictions exist within and span most watersheds. Each jurisdiction exercises a set of authorities that affect human uses of watersheds. Second, programs and management plans often target single problems, such as single sources or causes of water quality degradation, rather than addressing a complex of problems. Multiple jurisdictions and management plans and programs may work at cross-purposes, and in a number of instances fail to recognize and address critical problems.

As many scholars, practitioners, and commentators have noted, however, integrated, comprehensive management has not been adopted for political reasons. First, multiple overlapping jurisdictions jealously guard their powers and authorities, and are unwilling to have them weakened. Second, multiple conflicting interests exist concerning how and for what purposes watersheds should be managed. What emerges from strategic interactions among these multiple interests are single issue or single problem programs that fail to address a number of issues or balance different interests. Even when a multiple use mandate is granted an agency, the agency often struggles to make reasonable and workable tradeoffs among the multiple uses

(Clarke and McCool, 1985). Thus, for political reasons integrated, comprehensive management is difficult to achieve.

While watersheds are complex inter-related ecological and hydrological systems subject to diverse inter-related threats, comprehensive, integrated management at the watershed level in many cases is not politically or organizationally feasible. What then? Another approach, based on the Institutional Analysis and Development framework, begins from a very different starting point, at least in terms of institutional solutions. Rather than centralizing and integrating decision making, that is, instead of directly managing watershed ecosystems at the watershed level, the diverse inter-related threats to watershed ecosystems are addressed at their source - the actions of individuals and communities that cause these threats.

Community based responses to shared ecosystem threats are more likely to evolve if the boundaries of the problem and the boundaries of the community are roughly co-terminus. Community members can exercise some control over the problem, and in turn capture the benefits of solving it (Ostrom 1990, Tang 1992, Blomquist 1993). Active community involvement in identifying problems and institutional solutions to those problems contribute to well designed solutions that are perceived of as fair and legitimate. Individuals directly involved in a problem possess valuable time and place information that is necessary to craft rules that will fit the situation (McKean 1996). Furthermore, individuals whose behavior must change are more likely to accept a set of rules that they themselves participated in designing (Tang 1994). Monitoring, sanctioning, and conflict resolution mechanisms are vital as well for community based management. Monitoring and sanctioning mechanisms act to assure community members that those who are subject to the new set of rules are following those rules, and that rule-breaking behavior is being sanctioned. These assurances maintain support for participating in rule making activities and for rule following. However, honest differences among community members concerning implementation and enforcement do arise, and means for dealing with such conflict must be available to community members to keep conflict within reasonable boundaries. Finally, institutional solutions that communities devise to address shared problems are vulnerable to the actions of larger political jurisdictions within which communities reside (Pinkerton 1989, Ostrom 1990, Tang 1992). Thus, community based management is more likely to emerge in situations in which larger political jurisdictions are supportive of it (Blomquist 1993).

An increasing body of evidence suggests that community based approaches perform relatively well in addressing natural resource problems. In comparing communities that have organized themselves to address shared resource problems versus communities that have not, organized communities resolve numerous resource problems that unorganized communities do not (Schlager 1992, 1994; Tang 1992, 1994). In comparing community based management of natural resources with centralized agency or government management, community based management is more likely to effectively resolve numerous resource problems (Ostrom 1990, Tang 1992). The same findings hold for management systems in which centralized authorities share management with local communities versus centralized authorities that do not share management powers (Ostrom, Gardner, and Walker 1994; Tang 1992).

Community-based responses may be effective means of addressing a number of watershed problems, however, they cannot address all of the problems that threaten watershed ecosystems. First, problems may extend well beyond the boundaries of a particular community. Under such circumstances, communities are unlikely to address such problems because any actions that they take may have little effect on the problem, or they may not be able to capture the benefits produced by such actions. Second, communities may effectively address local problems over which they have some control, but in the process produce problems or externalize costs on surrounding communities. Third, adjoining communities and jurisdictions may work at cross-purposes with one another, further compounding watershed ecosystem degradation. Thus, while community based systems excel at addressing local scale problems, they falter in addressing regional scale problems. Furthermore, linked, or interdependent community based systems may collectively produce undesirable outcomes that hasten the demise of watershed ecosystems.

For the effective governance of watersheds to emerge these issues of scale and interdependencies need to be addressed. Ideally, the governance of watersheds would consist of a series of nested institutional arrangements. Jurisdictions and management programs would be designed to match the scale of the problem. Small scale problems would be addressed by local communities, regional problems by associations of communities, and watershed level problems by watershed level organizations. While this ideal set of governance structures is unlikely to be realized in practice, if we are to begin to move towards it, a number of fundamental issues must be addressed. One of the most important issues is human behavioral responses to different types of rules and regulations, and changes to those regulations. Another issue of equal importance is watershed ecosystems responses to human uses, as mediated by differing rules and regulations. In either case, a lack of basic information about human and ecosystem behavior is at issue. This project proposes to address these information and knowledge needs.

Approach

Arizona is one of the fastest growing states in the U.S. Much of that population increase is along or adjacent to rivers and streams, further endangering them. The Arizona Department of Water Resources estimates that Arizona has lost 90% of its riparian habitat. Rapid growth is gaining the increasing attention of citizens, interest groups, and local and state elected officials. The November 1998 ballot will contain several initiatives addressing growth and the environment (Arizona Daily Star, 3/14/98).

Within Arizona, three sites will be used for developing models of the interaction among human behavior, institutional arrangements, and ecosystem behavior. The upper reaches of the Santa Cruz River, the Rillito River, and the Rincon Creek. The latter two are located within the Santa Cruz River Watershed.

A comparative analysis and simulation of three sites in the same state and in the same watershed controls, or holds constant, certain characteristics, while allowing for the variation of other, central, characteristics. The three sites are located in southern Arizona, in the Sonoran Desert. They are subject to urban and suburban development pressures. They are governed by many of the same Arizona laws concerning real estate, zoning, and riparian protection.

On the other hand , *the three sites vary in critical ways. The* sources of stream flow vary. The

Upper Santa Cruz River is effluent fed. The Rincon Creek and the Rillito River are fed by storms and spring run off. The ecosystems of each site differ in the human pressure brought to bear on them. Rincon Creek's ecosystems are in relatively good health, but the area is planned for dense development in the next decade. The ecosystems of the Upper Santa Cruz River have undergone substantial changes over the past several decades. Degraded by ranching and agriculture, they are being restored as agriculture and ranching is being abandoned. However, this portion of the River is witnessing substantial residential development. The Rillito River, which flows through Tucson, Arizona, is completely engineered, including channelization, embankment stabilization, and flood plain infill and building. Finally, the institutional arrangements governing the development and use of water sources differ. Like many western states, Arizona law, with one exception, does not recognize the hydrologic connection between groundwater and surface water. Different bodies of law govern each type of water. This is true for the Rincon Creek and the Rillito River. The single exception to this is the Upper Santa Cruz River. In 1994, the Arizona legislature recognized the surface and ground water connections, and water along the riparian corridor, no matter if it is surface or ground, must be managed conjunctively.

These dynamic ecological and institutional variations allow for the exploration of the effects of institutional arrangements, human uses, and watershed ecosystem responses on restoration, protection, and enhancement activities.

Methods

The interactive effects of human uses, institutional arrangements, and watershed ecosystems will be explored by bringing together two formerly disparate, state-of-the-art approaches to address watershed-scale issues - intelligent agent based GIS software and the Institutional Analysis and Development framework. Intelligent agents moving across and exploring GIS landscapes have been used to simulate conflict that emerges among multiple users of natural resources. What such simulations have not included are the rules and regulations - the institutional arrangements — that govern and constrain the choices of intelligent agents. The Institutional Analysis and Development Framework is a systems framework that guides analysts in exploring and explaining human behavior in complex environments represented by interactions among institutional arrangements, ecosystems, and cultures. Institutional arrangements possess spatial and temporal dimensions, just as do natural systems, allowing them to be built into a GIS simulation. The Institutional Analysis and Development Framework includes a logic based grammar of rules that eases the translation of rules into computer code. Thus, by combining intelligent agent based GIS software and the Institutional Analysis and Development Framework, simulations of the interaction of human uses, institutional arrangements, and watershed characteristics and processes can be created. Such modeling will permit the exploration of complex human and natural interactions on multiple scales. Furthermore, these models will be designed so as to support local level, community based decision making.

The modeling effort proposed in this project differs substantially from existing modeling efforts in the social and natural sciences by 1) explicitly and directly incorporating human behavior and 2) representing human behavior in a realistic manner. In the social sciences, standard welfare economics and systems modeling efforts typically identify a problem, or series of problems, a value or mix of values to be optimized in solving the problem, and a set of rules or regulations, that if adopted, and perfectly followed, would optimally solve the problem. The implicit assumptions about human behavior in such models are heroic. First, the policy maker, or the regulator, is assumed to be a unitary actor, who will select a set of regulations that will optimize the designated values. In practice, regulations and policies are the product of strategic interactions among multiple decision makers (Scharpf 1997:5). Second, those individuals who will be subject to the regulations, that is, those individuals whose behavior is expected to change in response to the regulations, are assumed to be perfect rule followers. In practice, individuals devise and experiment with a wide variety of strategies, including rule-breaking strategies, within the context of a given set of regulations. Individually and collectively, those strategies may produce outcomes wholly unexpected and unintended by the regulators.

This is not to say that social science modeling efforts are of little value. Quite to the contrary, such modeling efforts are very good at identifying problems and possible solutions to problems. However, if what is of interest is understanding human responses to a set of regulations, or understanding the types of regulations likely to be adopted by strategic, interactive policy makers, then one must move beyond standard modeling efforts. In other words, standard models provide an excellent starting point for modeling human behavior, by identifying problems and solutions. But they do not adequately model human behavior. Other models must be developed to do that such as those proposed in this project.

In the natural sciences a significant body of work has been amassed over the years with regards to the modeling and simulation of natural systems, however, relatively little effort has been recorded in the modeling and simulation of human systems. Recently, the call has gone out from geographers (Openshaw 1995) and sociologists (Doran and Gilbert 1994) for increased efforts to be devoted towards the development of human systems modeling as a discipline. A number of research efforts have emerged recently (Gimblett and Itami 1997, Doran and Gilbert 1994, Holland and Miller 1991) which explore modelling and simulation with human systems applications.

The rapid development of accurate spatial databases using GIS has opened opportunities for resource scientists to extend the use of this data by integrating GIS with emerging technologies. Exploratory studies by (Berry et al. 1993; Gimblett et al. 1994; Saarenmaa et al. 1994; Flynn 1997) and many others have incorporated artificial intelligence optimization techniques, such as neural networks, genetic algorithms and expert systems, with GIS for studying landscape level problems. There is also a growing interest in using GIS to model spatially-explicit dynamic processes (Gimblett et al. 1994; Green 1989; Slothower et al. 1996; Deadman et al. 1993; Deadman and Gimblett 1994; Briggs et al. 1996; Stockwell and Green, 1989).

The use of Individual-Based Models (IBMs) is one approach to modeling spatially-explicit ecological phenomena. IBMs, according to Slothower et al. (1996), are "organisms-based models capable of modeling variation among individuals and interactions between individuals." IBMs offer potential for studying complex behavior and human/landscape interactions within a spatial framework. Since spatial information about a phenomena is stored on a georeferenced coordinate system, space within a grid is implicit and relative to the origin of the grid (Slothower et al. 1996). IBMs offer some basic advantages over some current spatial modeling techniques such as cellular automata. Since space is continuous and individuals are represented independent of the environment, temporal and spatial variability can be handled asynchronously. The modeler has the ability to define an individual's goals, abilities, and interaction rules, when encountering other individuals.

One form of individual-based modeling that has been gaining popularity in a variety of disciplines focuses on the development of artificial intelligent agents. Intelligent agents are self-contained, autonomous objects that reside within a virtual world created by the simulation. These agents have two basic components; a model of their world, which is created through interactions with the environment, and a model of themselves, which includes individual strategies and utility functions (Ziegler 1990). A variety of simulation toolkits are being developed to provide researchers with a mechanism to study intelligent agents. Examples of such tools include Swarm (Hiebeler, 1994, Minar et al. 1996); Echo (Jones and Forrest 1993; Forrest and Jones 1994); GENSIM (Anderson and Evans 1995) and RBSim (Gimblett, 1998). In simulations using these systems, individual agents are developed to represent the distinct individual actors in the real world system being studied. Researchers are frequently interested in studying the behavior of the overall system that emerges as a result of the many actions and interactions of these agents.

But it has only been recently that researchers seeking new ways to understand human/environment interactions have been exploring simulation as a tool for developing models of human behavior. Recent studies by Drogoul and Ferber 1995; Findler and Malyankar 1995; Conte and Castserfranchi 1995, clearly demonstrate the potential for agent-based modeling techniques to examine human/landscape interactions. These studies utilize a general model of multi-agent simulations based on computation agents that represent individual organisms (or groups of organisms) in a one to one correspondence. These studies seek to understand the process of evolution in the study of ecological and sociological systems. As Drogoul and Ferber (1995) state "we are interested in the simulation of evolution of complex systems where interactions between several individuals at the micro level are responsible for measurable general situations observed at the macro level. When the situation is too complex to be studied analytically, it is important to be able to recreate an artificial universe in which experiments can be done in a reduced and simulated laboratory where all parameters can be controlled precisely."

Two recent modeling efforts at the University of Arizona have utilized an intelligent-agent based approach to developing human systems models with resource management implications. These models will comprise the foundation for the model that is proposed in this study. One of the modeling efforts at Arizona developed a series of intelligent-agent based simulations of the common pool resource (CPR) management experiments documented by Ostrom et al (1994). In these CPR simulations, individual agents were created, with their own set of unique characteristics, to represent individual participants in the experiments and the common pool resource itself (Deadman 1997). The agents in these simulations possessed adaptive capabilities based upon theories of induction (Holland et al 1986) and the ability to communicate with one another. These simulations have shown considerable potential in their ability to validly replicate the behavior of human subjects in laboratory settings (Deadman 1997). In addition, the agent based modeling approach is structurally similar to the Institutional Analysis and Development (IAD) framework described by Ostrom et al (1994).

Another simulation developed at Arizona utilizes an agent-based approach to explore human/landscape interactions in a GIS environment. The Recreation Behavior Simulator

(RBSim) simulates the behavior of human recreators in high use natural environments over time (Gimblett, 1998; Gimblett and Itami 1997; Bishop and Gimblett 1998). RBSim utilizes spatial data and their operational algorithms, derived from a geographic information system, to provide agents with the ability to read, analyze and interpret environmental data in relation to their own internal models. These internal models were developed, in part, from an on-site visitor use survey that acquired data on recreational use, desired beneficial outcomes and conflicting recreational uses. RBSim represents the first seamless integration of a geographic information system and an intelligent agent based simulation system.

The simulation proposed here will combine the agent-based institutional modeling experience gained from the CPR simulations with the advanced spatial modeling capabilities of the RBSim simulation approach. The proposed project intends to develop a prototype that will improve understanding and integration of physical, biological, and human interactions in semi-arid ecosystems at multiple spatial and temporal scales. We will utilize intelligent-agent based simulations in GIS environments to explore human-landscape interactions and their impacts on riparian ecosystems.

In order to explore the objectives outlined above, we have selected three study sites: The Santa Cruz watershed and the Rillito will both be used to develop our baseline models. Both of these study sites have been severely impacted overtime both from natural and man-made causes. The Rillito provides us with the opportunity to model the effects of completely re-engineering - little consideration of setting limits with regards to impacts; Santa Cruz has undergone particular types of uses, protections and there is strong evidence of the consequences of these actions over time. Both of these study sites provide ideal opportunities to study social impacts. The model will be developed using both of these sites and then applied on the third study site that falls within the Rincon Creek Watershed to examine the question of what will be the impact to the Rincon Creek with increasing pressures from development. What can be done to rehabilitate the Rillito? In order to answer these questions the project will be constructed around the following activities:

This project involves the following steps, each will be described in further detail below:

1. Acquire and Build the Spatial/Tabular data for the study sites
2. Develop procedures for measuring land use change in the Upper Santa Cruz River and Rillito River
3. Develop conceptual model' for predicting impacts of land use changes on the Upper Santa Cruz and Rillito Rivers' Riparian Ecosystems
4. Develop and Test Alternative Development Scenarios for the Rincon Creek and Rillito River
5. Develop Institutional and Agent Based Simulation Systems
6. Develop intelligent agents that communicate
7. Convert models to be interactively utilized over the WWW

<u>1. Acquire and Build the Spatial/Tabular data for the study sites:</u>

The interaction of watershed response and land-use will frequently be modulated by the effects of climatic change and variability. Thus in some situations the impact of land use change may only become fully apparent when the watershed responds to extreme events or climatic discontinuities, while in other cases it may be difficult to disaggregate the effects of land use change from those of climatic variability. It is therefore important to consider the complex interaction of both sets of potential forcing factors when reconstructing long-term changes in watershed response.

The interaction of land use and climatic variability has further dimension. Climate change may induce land use change, by making a certain land use or land-use practice either possible or impossible. If people change land uses approximately in phase with climatic changes, then changes in watershed response will be a result of both. But if people thrive by making no change to their land use, then changes in watershed response will be to the climatic change only. The identification of causal linkages between watershed response, land use, and climate variability, is, therefore, not necessarily straightforward.

For example, in a natural (i.e. undisturbed) watershed that is tectonically stable, climate change and autocatalytic factors within the watershed (e.g. gradient) will produce a change in sediment yields. The superimposition onto the undisturbed watershed of land use (clearing, grazing, cultivation, urbanization) adds a new control on sediment fluxes. Once land use has been superimposed, further climate changes will lead further land use changes, but via the decision making processes of people. So the new land use change may or may not reflect the new climate.

Furthermore, these interactions are different at different spatial scales, so that land use effects are often dominant at small scale (i.e. in small headwater watersheds) but become less important than climate-driven hydrologic changes as watershed area increases. But land use change may in turn reflect climate if land user's decisions were a response to climate change. Further downstream, a stream can produce changes that are the result of coupled transport systems upstream, for example, hillslopes coupled to streams (Humphrey and Heller, 1995). Linked erosional and depositional systems may include feedbacks that result in internally governed oscillations. These oscillations may be reflected as, for example, quasi-periodic deposition and erosion on a floodplain, unrelated to external causes such as the complex responses described by Schumm (1977). An external perturbation to such a coupled system, from climate or land use change, can produce complex patterns of watershed response that again cannot be readily related to a specific cause.

Therefore, to evaluate the effects of land use and climatic variability interactions on watershed response for the Santa Cruz, Rillito and Rincon Valley watersheds, our conceptual modeling system will incorporate linked model components of climate (precipitation, temperature), vegetation, soil, streamflow generation and sediment yield. These will be used as indicators to measure changes that have occurred overtime. A significant amount of this data already exists in digital form for all study sites. For example, historic aerial photographs date back to the early 1950's for the Santa Cruz, Rillito and Rincon valley. Historic aerial photos will be used to extract land use data and measure the changing patterns overtime. This land use data will be used in the conceptual model to measure the spatial changes that have occurred in each of the study sites at the watershed scale. The assumption in the conceptual model is that the more landuse/landcover changes that occur at the watershed level, the more local impacts will occur in each of the streams. For this reason, ground water monitoring, plant inventory, channel morphology, stream flow and sediment movement monitoring data will be used for each of the streams for some ten to twenty years. This data will be used in the conceptual model to measure the changes that have occurred to the Santa Cruz, Rillito and Rincon Creek rivers. Land ownership, census data, political jurisdictions, local land development policies, regulations, water laws and ordinances are available for each of the watersheds and will be categorically assembled into a digital database for model development. This data is imperative to begin to understand the jurisdictional changes and particular policy changes that have occurred overtime which ultimately effect the land use patterns and resulting impacts on the streams and rivers.

2. Develop Procedures for Measuring Land Use Change in the Santa Cruz Watershed and Rillito
Spatial statistical procedures will be used on the aerial photographs to measure the amount of changes that have occurred to both the Santa Cruz and Rillito study areas overtime. The data will be used to assess the type and amount of land use change, with particular attention given to the percentage of impervious surfaces in each of the area. All orthographic photos are georeferenced and rectified using permanent GPS monitoring points that have been established in earlier baseline studies. Images that have been rectified to a high degree of precision with the permanent monitoring points will be used to extract spatially distributed data. Repeating this procedure for several years may provide a statistically reliable method for assessing land use change. In particular, the analysis will focus on the extent of new development as described by the area occupied by impervious surfaces (roads, houses etc.).

3. Conceptual Model Development for Predicting Impacts of Land Use changes on the Upper Santa Cruz and Rillito River's Riparian Ecosystems

A conceptual model is developed for this study which incorporates the use of optimization techniques (neural networks (NN)), GIS and long term monitoring data to develop a tool to predict the impact of changes to the riparian ecosystems in both the Santa Cruz and Rillito study sites. NN's are being used in many fields where problems cannot be efficiently solved using traditional approaches. NN's have the ability to learn patterns overtime and provide optimal results to complex dynamic problems. They have been successfully used by (for example by Skirvin et al. 1997; Zhang et al. 1997) to classify aerial photos, airborne videography and landsat TM data. Others (for example Deadman et al. 1997; Guisse et al. 1997) have successfully used them in conjunction with GIS to predict changes in land use patterns. NN's in this study will be trained to recognize changes in land use patterns, changing conditions along the riparian areas for each of study sites and policy changes, regulations and water laws. The assumption behind the model is that by understanding both the changes in land use/cover conditions in the watershed surrounding the riparian area and the cause and effect changes to the site specific conditions of the creek over time, a model can be constructed to predict changes to the natural conditions of the rivers or creeks. As more data is collected over the years at these specific study sites, change can be monitored and increase the predictive capability of the model. With these assumptions in mind, this model utilizes the patterns and relationships of physical measurable variables that include a range of conditions of the riparian system; the current land use conditions that surround and influence the riparian system ie. watershed; and the corresponding changes in policy, regulations and water laws in each of the study sites sampled.

There are three data inputs into the conceptual model. These three components are the biophysical (global scale), riparian systems expert-judgement and experimental systems field work (local scale) and policy changes, regulations and water laws. The biophysical component affects or alters the amount of vegetation and development. Existing conditions or proposed changes to those conditions provide geographic information to the neural net classifier.

At the center of the model is the NN classifier. With the input supplied by the three riparian system monitoring components to the NN classifier, riparian health and productivity can be assessed. A workshop will be held by the Rincon Institute (list collaborator) to bring together scientists, local residents and community representatives who both study, manage and use riparian ecosystems to define indicators which represent conditions of the riparian ecosystem. The results of the workshop will be recorded and used as output in our adaptive neural network. The indicators are well represented in the data collected and used in this study. Each of these components measures change to the system. The following are the components of the NN model:

1. Current Measure of Land Use/Land Cover Patterns (percentages) in Santa Cruz Watershed from
aerial photos
    - land use/cover (landuse classification, native vegetation vs planted -1 node for each community type) - Lct
    - vegetative cover - Lcl
    - vegetation density - Ldl
    - percentage of impervious surface - Is
    - percentage of development - Dc
    - political boundaries - pj
    - water laws and regulations - od+
    - roads (infrastructure) - Rl

2. Vegetative species, percentage cover and density per monitoring stations along Santa Cruz River-S1s, S1c, S1d
3. Streamflow data per Experimental Site - Sf
4. Sediment Movement data per Experimental Site - Sm
5. Groundwater data per Experimental Site - Gw
6. Precipitation - p1
7. Temperature - tl

Model outputs will be a measure of health and/or productivity of the riparian system. This is expressed as scalar set of thresholds that range from 1 to 10, defining the heath of the system. For the initial training of the neural net based model, conditions ranging from ideal to impaired must be defined for the riparian system. Since little is known about these relationships the research team will define what constitutes a healthy riparian system, in terms of the type of measured variables described earlier in this report. A set of physical patterns or interaction rules that explicitly define the contribution of each variable to the scalar output will be derived. For example, under ideal conditions there would be <u>no development</u>, <u>100% vegetative cover</u>, <u>stream flow</u> and <u>sediment movement</u> may be high, but the health of the riparian system may be excellent in terms of productivity, regeneration and seed production. This rule would be described like this:

Global Indicator Variables	Specific Indicator Variables	Riparian Condition Output

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(R1 Lct Lc1 Ld1 Is Dc Sh PJ od+ t1+p1)    (S1s S1c S1d ...Sf Sm Gw)      (Heath/Productivity Index)
 |-------------------------------------| + |------------------------| = |-----------------------|
 0 80 80 40 10 20 13 3 1 4 5                 1 30 30 ... 40 40          0 0 0 0 0 0 0 0 0 1
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where 0 represents development, landcover type mesquite, Percentage of vegetation coverage (80%), vegetative density (40%), Infrastructure (10%), Percentage of Development (20%). Experimental Site variables vegetation species (type 1), coverage (30%), density (30%), streamflow (40cfs), Sediment movement (40), Depth to groundwater (2m), Precipitation (10in), Temperature (80). These as a pattern represent some condition of the riparian system. The next ten values represent the current condition of the riparian system for each of the sites. The associated pattern combined represented in this case a healthy productive system. The first 0 of the riparian condition output represents a unproductive/severely damaged riparian system and the 10^{th} node or value 1 represents a healthy/productive system. In this case the 10^{th} node is turned on which represents the later. Another way of describing this pattern is like a rule. This rule will be true only:

if the following conditions are encountered in one of the sites:

0 80 80 40 10 20 13 1 30 30 ... 40 40 2

set it equal to the 10^{th} output variable or in this case 1 which represents a healthy system

0 0 0 0 0 0 0 0 0 1

Conversely, if the following pattern is encountered, which indicates 100% development and no remaining vegetation, then:

0 0 0 40 10 100 1 30 30 ... 40 40 2

set it equal to the 1^{st} output variable:

1 0 0 0 0 0 0 0 0 0

There are potentially thousands of combinations of rules that can be derived from the measured data on site. The neural net will be trained to associate the input patterns with the output patterns.

Training the Neural Network to Recognize Riparian Conditions

Trained on optimal set of controlled combinations of variables outlined above that represent each of the riparian health/productivity conditions. These patterns will represent both optimal to suboptimal conditions based on knowledge acquired by the Rincon Institute and described earlier for riparian systems and data extracted from time series aerial photographs which represent a range of land use change conditions. Using change detection as an indicator of impact, these time series data should reveal the declining conditions of the riparian ecosystem as a result of land use change.

The NN will then be tested on the data from both the global set of site variables (watershed scale) and from microscale experimental field data collected from each of the experimental sites.

The data will be analyzed by the neural net model to predict current heath/productivity conditions for each of the study sites. These results will be evaluated, training samples and outputs adjusted and the network will be additional trained to recognized and adapt to these new patterns. The purpose of this method is to first identify how accurate the network can predict the current conditions of the study sites based on the expert-based judgements of their conditions. Second, to increase the knowledge base and refine the predictive capability of the neural network by retraining on the data captured in the field.

4. Alternative Development Scenarios for the Rincon Creek Watershed and the Rillito River.

Thus far, the models consist of a GIS for each study site, and neural networks for each study site that introduce dynamic temporal and spatial capabilities. Once the Rincon Creek model is validated it will be used to examine alternative development scenarios. These scenarios can be grouped into two categories. The first category consists of the existing plans for development that have been approved by the Pima County Board of Supervisors, and variations on those plans that were offered as alternatives to the Supervisors by the Pima County Planning Department. This category of alternative development scenarios is a matter of public record and we possess copies of these plans.

The second category consists of alternative development scenarios created by the current residents and users of the Rincon Creek Watershed. The Rincon Institute, which for the past several years has been holding meetings with residents of the watershed, will hold two study sessions. All residents, landowners, and recreational users will be encouraged to attend and participate in both sessions. During the first session, three or four development scenarios will be created. By developing several scenarios a mix of interests and values can be captured without having to attempt to reach consensus among the participants on a single scenario. During the second session, the scenarios developed in the first session will be run, and the results explained and shared with the community participants. Refinements will be made to the scenarios.

A set of landuse scenarios will be developed for the Rillito River. These scenarios will explore the effects of different types of land and water use rules and regulations for rehabilitating and recovering riparian areas along the river. Furthermore, as is currently the case with the Upper Santa Cruz River, the use of effluent and other sources of water to support stream flow and habitat recovery will be explored.

The alternative scenarios will be incorporated into the GIS model by reducing them to a set of rules that will be assembled into the data base.

5. Development of Institutional and Agent-Based Simulation Systems

As we argued above, many modeling efforts either neglect human behavior or make heroic assumptions about how humans will behave. Consequently, many models do not assist citizens and public officials in understanding the likely responses of individuals' to alternative sets of rules and regulations, and the consequences for ecosystems of those human responses. Furthermore, once individuals gain some experience with a given set of regulations, and understand the human and ecosystem responses, they in turn change their behavior, they pursue new strategies to better achieve their own goals. Thus, the situation is dynamic, making it that much more difficult for citizens and public officials to predict the consequences of a change in regulations.

Our models, to this point in the project, share these same weaknesses concerning human behavior. In incorporating and running the alternative development scenarios in step 4, we make heroic assumptions concerning human behavior. We assume that the rules as they appear in planning documents, and as expressed by residents and watershed users, will be flawlessly implemented, and once implemented, will be perfectly followed. No mistakes, no rule breaking, no unintended or unforeseen consequences are allowed. We propose to remedy these weaknesses in our models by explicitly incorporating intelligent agents. The agent-based simulation system will be modeled after the RBSim program discussed earlier. The simulation environment will comprise the GIS data base including the neural net classifier. The system will be programmed using Visual Basic 5.0, a fully object-oriented language that allows for agents to interact with their environments and communicate with each other. This environment will provide the agent with the ability to directly read the GIS database and all the inherent information it has stored, including rules and regulations. Furthermore, the agents can query the NN classifier about the current state of the watershed ecosystems.

The intelligent agents will be based on the model of the individual found in the Institutional Analysis and Development Framework (Ostrom, Gardner and Walker, 1994), and used in the intelligent agent simulations by Deadman (1997). The model of the individual consists of four parts: 1) preferences, 2) information processing capabilities, 3) resources, and 4) selection criteria. Preferences refer to the tastes of an individual (McEachern 1991). In a watershed setting, individuals may prefer open spaces, or close neighbors, or a mix of wildlife, etc. Information processing capabilities represent the cognitive abilities of individuals. The rational actor in microeconomic theory is assumed to be an infallible processor of information, whereas boundedly rational actors, as portrayed by Herbert Simon (19xx), are limited in their processing capabilities. In order to realize their preferences, individuals must possess resources, which consist of time, money, expertise, and so forth. Finally, individuals use criteria to select among alternative courses of action. Individuals may attempt to maximize their well-being, or they may satisfice, and select an action that meets or exceeds some threshold (Simon 19xx; Ostrom, Gardner, and Walker 1994).

These four different components of the model of the individual can be given a wide variety of values and then combined in many different ways, leading to substantial variation in behavior that could be difficult to interpret. For the baseline models in this project, we will set these four components, and not allow them to vary over time. We will assign a fixed set of preferences to each intelligent agent. We will provide each type of intelligent agent with the resources necessary to take a variety of actions in relation to the use of their property. We will assume that individuals will take actions that they believe will make themselves better off. That is, an individual is assumed to choose an action if the individual believes that the benefits of that action outweigh the costs of that action for the individual. Finally, we assign individuals complete information individuals have complete knowledge of the environment in which they operate, i.e., they know the state of the ecosystems and they know the rules and regulations that they are subject to, and they know one another's preferences (Ostrom, Gardner, and Walker 1994). However, they do not know all actions taken by all participants (Deadman 1997).

We will create four types of intelligent agents « land developers, ranchers, land owners, business owners, and recreationalists. Each type of agent will be assigned a fixed set of preferences unique to its type. For instance, land developers will be assumed to prefer that land be developed and not remain idle or undeveloped. Recreationalists will be assumed to prefer open space and relatively unimpeded access to land, and so forth. Each type of agent will be assigned resources that allow it to take a wide variety of actions. Ranchers will possess sufficient resources to run as many or as few cattle on their land as they choose. Developers will possess sufficient resources to develop their land as densely as they choose. Finally, to assign these agents complete information they will be able to query one another, and to query the NN classifier for information concerning the landscape.

Intelligent agents act so as to realize their preferences, and in so doing, make themselves better off. Individuals adopt and experiment with different sets of actions or strategies. Strategies, similarly to rules, consist of a logic based grammar and thus, they are readily programmed (Deadman 1997).

The preferences and strategies of the intelligent agents will be constructed from actions and choices that developers, ranchers, land and business owners, and recreationalists have made. The sources of these revealed preferences and strategies are several. First are environmental conflict resolution simulations. The Udall Center for Studies of Public Policy, as part of its mission, creates and runs environmental conflict resolution simulations. For the purposes of this project, the Center is creating a watershed conflict scenario in which community members will participate. The scenario centers around conflicting uses of a moderately sized watershed. The participants include developers, ranchers, environmentalists, business people, land owners, and recreationalists. These positions will be played by developers, ranchers, environmentalists, business people, land owners, and recreationalists drawn from Tucson and the surrounding communities. The playing of the scenario will be recorded. Transcripts will be made, and the expressed preferences and strategies that players articulate will be derived. The Udall Center will run two of these scenarios.
Preferences and strategies of individuals will also be determined through the public statements and actions of individuals. The Pima County Board of Supervisors, and the Pima County Planning Board record their public hearings. We will identify those hearings at which individuals request variances to zoning and to the master plan of Pima County. We will identify the preferences expressed by the individuals participating in the hearings. Finally, we will examine the records of the City of Tucson and Pima County Planning Departments, and the Department of Water Resources for citations given for failing to obtain appropriate building permits, or for illegal taking or using of water. The citations document actions and strategies, albeit illegal ones.

A repertoire of strategies will be assigned each intelligent agent from which the agent may choose (Deadman 1997). Mechanisms by which intelligent agents evaluate their strategies will be devised. These mechanisms will allow the intelligent agents to query the neural net classifier, each other, and data bases that assign economic values to actions. Intelligent agents will then respond by following their existing strategies, or experimenting with new ones.

Intelligent agents will be placed in the alternative scenario environments characterized above in step 4. The watershed landscapes that the intelligent agents create will be compared with the landscapes created by the alternative landuse scenarios created in step 4 without intelligent agents. The landscapes from step 4 and step 5 will be compared using the spatial statistical procedures of step 2.

6. Development of Intelligent Agents that Communicate

To this point, intelligent agents make choices about the actions that they take independently of one another. They do not communicate. Agents will be given the ability to communicate with one another. Deadman (1997) has developed and explored the properties of different communication mechanisms for use by intelligent agents. Communication will allow the agents to exchange strategies and potentially coordinate their actions so as to achieve better outcomes for themselves. Intelligent agents that communicate will be placed in the environments outlined in steps 4 and 5. The watershed landscapes that intelligent agents that communicate create will be compared with the landscapes that intelligent agents that cannot communicate create.

7. Convert Agent-Modeling System to be interactively utilized over the WWW.

The agent modeling system for the three study sites will be converted to Java for distribution and experimentation over the web. All parameters will be built in to provide the user to experiment with various types of land use configurations, resulting impacts and community interaction and control over the management of the watershed.

Expected Results or Benefits

The project will develop cutting edge natural and social science that has immediate and direct application to watershed problems. The project will develop 1) a method for integrating natural and institutional systems in a GIS format with intelligent agents, 2) approaches for examining and detecting unintended consequences of institutional arrangements and individual behavior, 3) approaches for examining and detecting emergent properties of complex and interdependent systems, 4) a GIS based decision support and simulation system, for use by all members of the community, designed to model patterns in development, and resultant environmental changes, under different planning policy conditions, and 5) develop a virtual community center on the web which will include decision support models that may be run interactively over the web, a GIS allowing maps of the areas to be displayed, the database of natural and social systems information, background information, and links to local officials and institutions.

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